Neutrino Physics I

CTEQ Summer School 2011

Madison, Wisconsin

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Fermilab

Introductions First

Who am I?

- A neutrino physicist working at Fermilab
- An experimentalist
- Research background in neutrino oscillation experiments (MiniBooNE) and low-energy neutrino interaction experiments (MINERνA)

As an experimentalist, will tend to focus on an experimental history of the field and a qualitative understanding of key effects

Introductions First

Who is a neutrino?

- Most abundant matter particle in the universe, outnumbering protons, neutrons and electrons by a huge factor (~10^8)
- The only known component of dark matter in the universe (a few %)
- Neutrinos are critical to the dynamics of stars. Flux at earth produced by the sun about 66×10^9 cm^{-2}s^{-1}
- Carry 99% of the energy produced in a supernova
- Large numbers produced at the Big Bang still whizzing around the universe, “relic neutrinos” ~400/cm^3
- Even a banana is a prolific contributer to the neutrino content of the universe at the rate of ~1 million per day (radioactive potassium decay)

In order to understand the universe that we live in, it looks like we’ll need to understand the neutrino

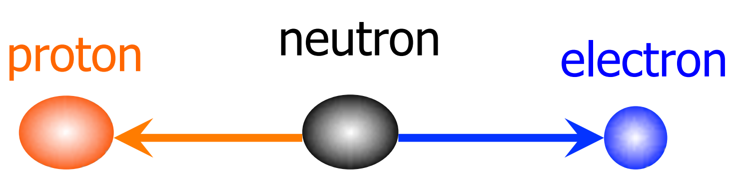
What's Our Plan?

- Lecture I
  - Birth of Neutrino Physics
  - Some Basics of the Weak Interaction
  - Neutrinos as a Probe of Matter
- Lecture II
  - Early Experimental History – Big Challenges and Bigger Surprises
  - Neutrino Oscillations, Masses and Mixing
  - Open Questions in the Neutrino Sector

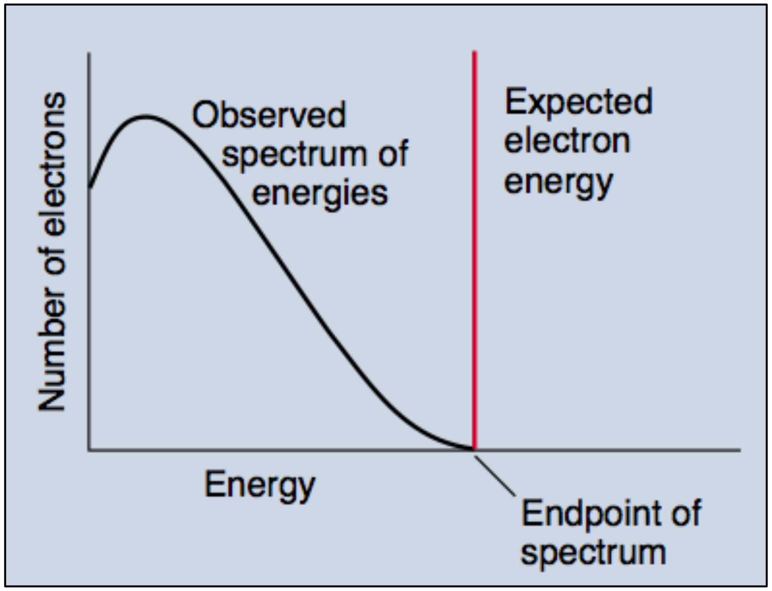
General Goal: To provide you an introduction to the basic vocabulary and concepts needed to understand current efforts and future results in neutrino physics

1930s: A Crisis in Particle Physics

- By 1931, it was well known that nuclei could change from one variety to another by emitting a “beta particle” (electron)
- But a 2-body decay should yield a monochromatic β spectrum
- Some even considered abandoning the conservation of energy!



$$(A,Z) \rightarrow (A,Z+1) + e^{-}$$



A “Desperate Remedy”

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum. I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant... ....

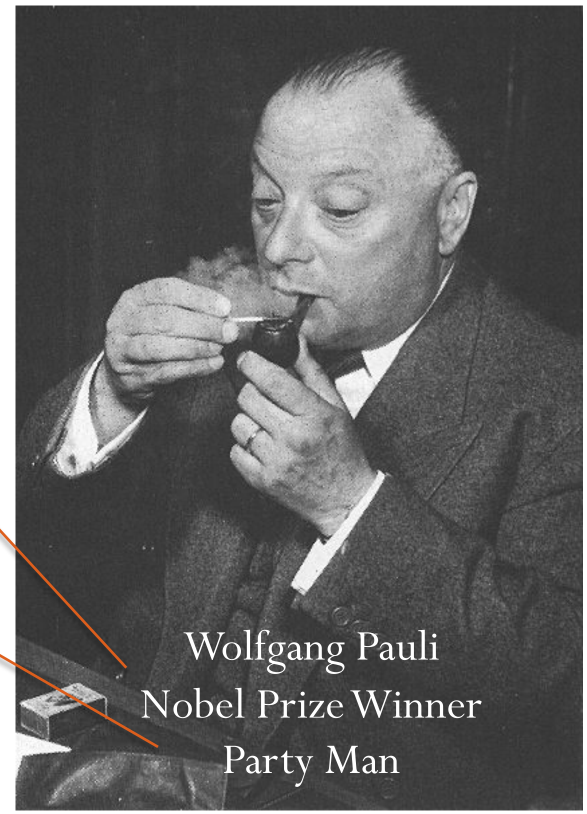
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant,

W. Pauli

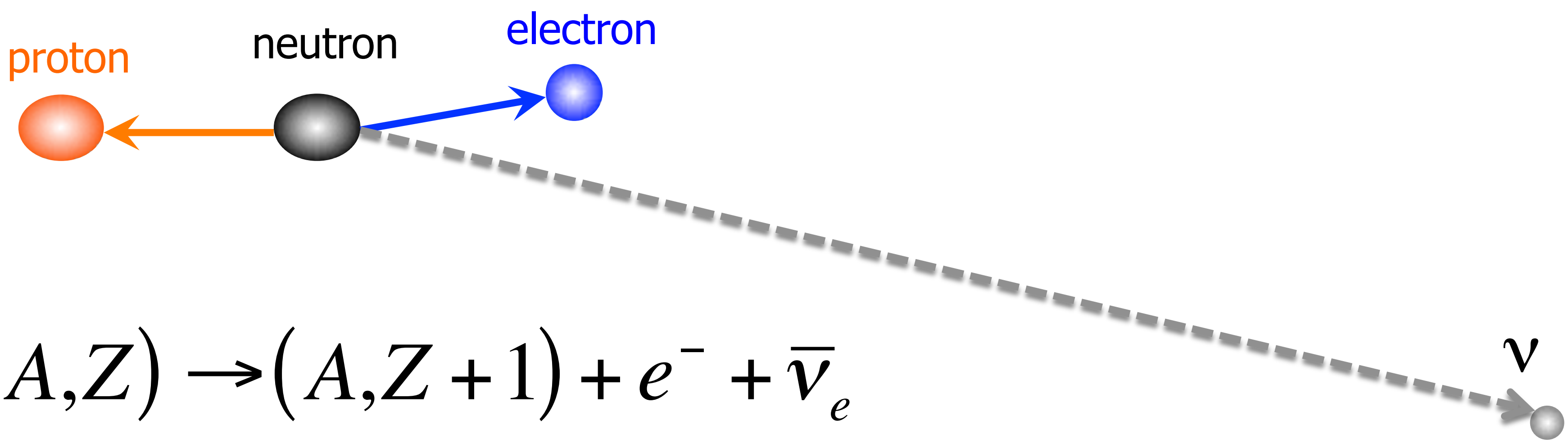
“wrong statistics” and “exchange theorem” refers to a second problem that:

$$n_{spin-1/2} \not\to p_{spin-1/2} + e_{spin-1/2}$$



Wolfgang Pauli
Nobel Prize Winner
Party Man

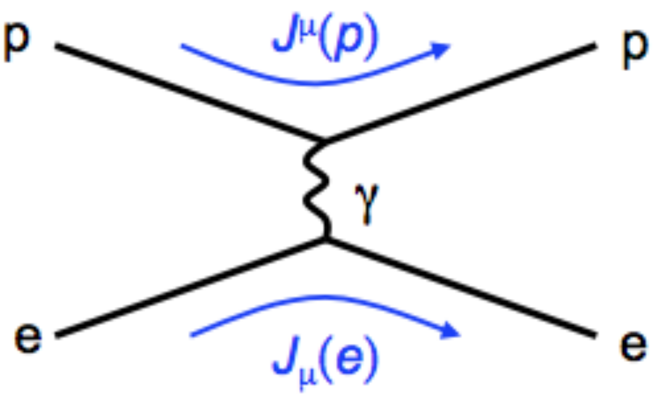
A "Desperate Remedy"

- Of course, we now know Pauli's "neutron" to be the electron antineutrino
- Spin-1/2 fermion, solves both the statistics and energy problems
- But can we detect it?
- 

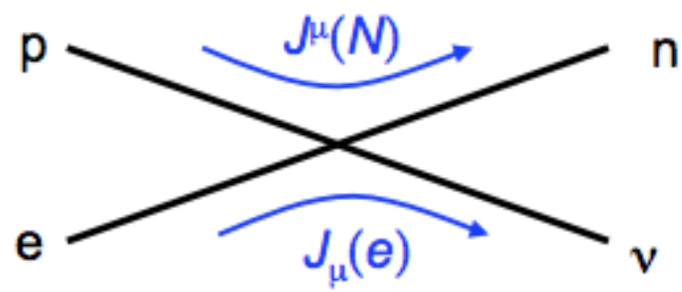
$$\left(A,Z\right)\rightarrow\left(A,Z+1\right)+e^{-}+\bar{\nu}_{e}$$

Fermi's Weak Interaction

- Enrico Fermi (1932), to explain the observed β-decay, developed the first model for weak interactions inspired by the success of the "current-current" description of electromagnetic interactions:



A point interaction of
four spin-1/2 fields



$$M_{em} = \left(e\bar{u}_p\gamma^\mu u_p\right)\left(\frac{-1}{q^2}\right)\left(-e\bar{u}_e\gamma_\mu u_e\right) \qquad M_{weak-CC} = G_F\left(\bar{u}_n\gamma^\mu u_p\right)\left(\bar{u}_\nu\gamma_\mu u_e\right)$$

Fermi's Weak Interaction

- Note the inclusion of Fermi's coupling constant, G_F

$$M_{weak-CC} = G_F\left(\bar{u}_n\gamma^\mu u_p\right)\left(\bar{u}_\nu\gamma_\mu u_e\right)$$

- G_F is not dimensionless (GeV^{-2}) and would need to be experimentally determined in β-decay and μ-decay experiments

$$\frac{G_F}{(\hbar c)^3} = \sqrt{\frac{\hbar}{\tau_\mu}\cdot\frac{192\pi^3}{(m_\mu c)^5}} \approx 1.166\times 10^{-5}/GeV^2$$

Fermi's Weak Interaction

- Bethe-Peierls (1934), using Fermi's original theory and the experimental value of G_F, were able to calculate the expected cross-section for inverse beta decay of few MeV neutrinos:

$$\nu_e + n \rightarrow e^- + p \qquad\qquad \bar{\nu}_e + p \rightarrow e^+ + n$$

$$\boxed{\sigma_{\bar{\nu}p} \approx 5 \times 10^{-44}\, cm^2 \quad for \quad (E_{\bar{\nu}} \sim 2\ MeV)}$$

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atomic mass unit

$$\boxed{d_{lead} = \frac{1.66\text{x}10^{-27}\ \text{kg}}{(\sigma_{x\text{-}N}\ \text{m}^2)(11400\ \text{kg/m}^3)}}$$

ν-N cross-section

density of lead

Hmmm… that looks small

What's the mean free path of a neutrino in lead?

Fermi's Weak Interaction

A typical neutrino produced in a power reactor or the core of the sun has 1-10 MeV of energy:

$$\sigma \sim 10^{-44}\ cm^2, \quad d_{lead} \sim 10^{16}\ m$$

over a light year of lead!

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better, but still around a billion miles of solid lead!

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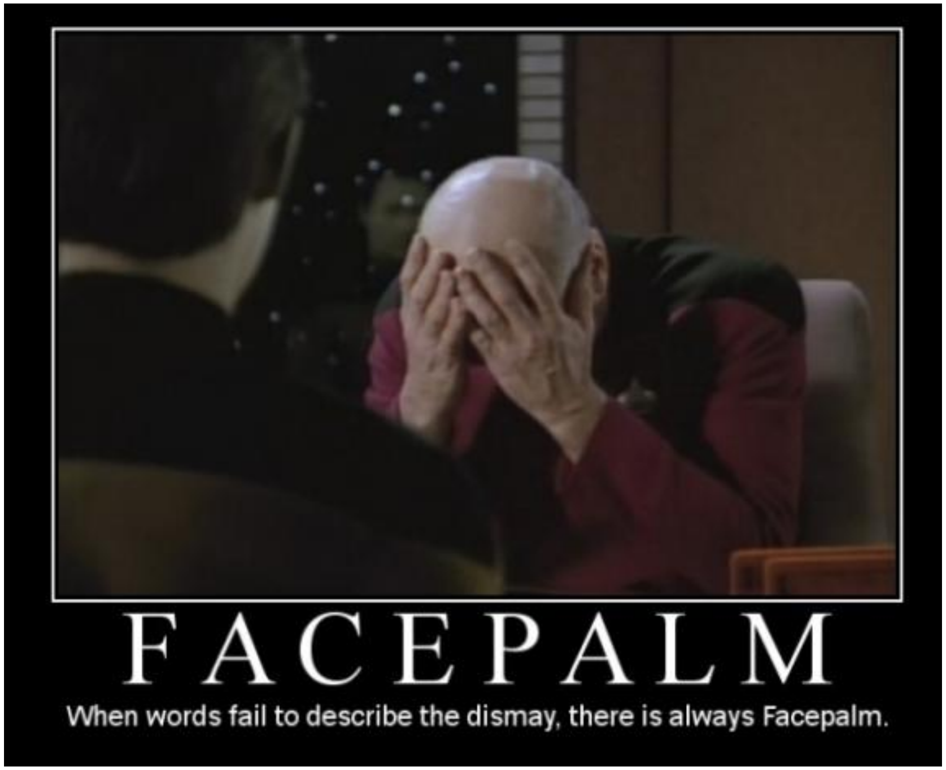
What about a proton with ~1 GeV of energy?

$$\sigma \sim 10^{-25}\ cm^2, \quad d_{lead} \sim \underline{10\ cm}$$

Pauli's Despair

The expected huge difficulty in detecting a neutrino led Pauli to famously quip :



"I have done something very bad by proposing a particle that cannot be detected; it is something no theorist should ever do."

- **Wolfgang Pauli (1931)**

Could the tiny cross section be overcome?

Project Poltergeist

To detect a neutrino, need an extremely intense source to compensate for the tiny cross section

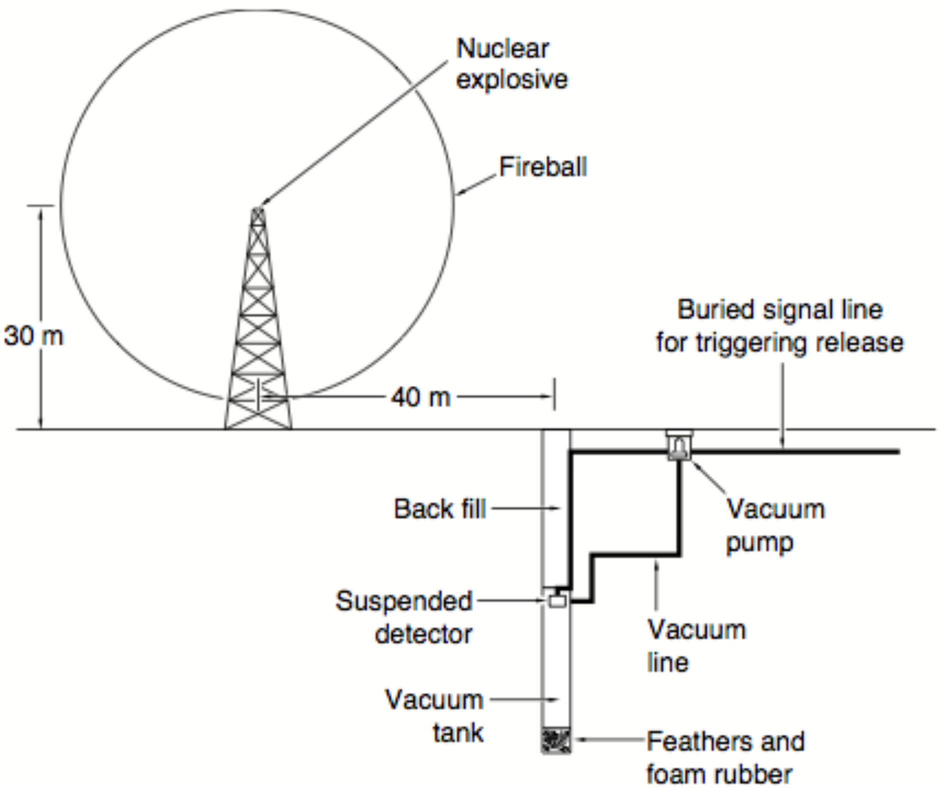


Figure 1. Detecting Neutrinos from a Nuclear Explosion

Straightforward plan

1. Explode nuclear bomb
2. Simultaneously drop detector to feather bed
3. Detect neutrino
4. Repeat??

Persistence Pays Off

To detect a neutrino, need an extremely intense source to compensate for the tiny cross section

- Solution: nuclear power reactor fission chain:

$$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e \rightarrow (A,Z+2) + e^- + \bar{\nu}_e \rightarrow \ldots$$

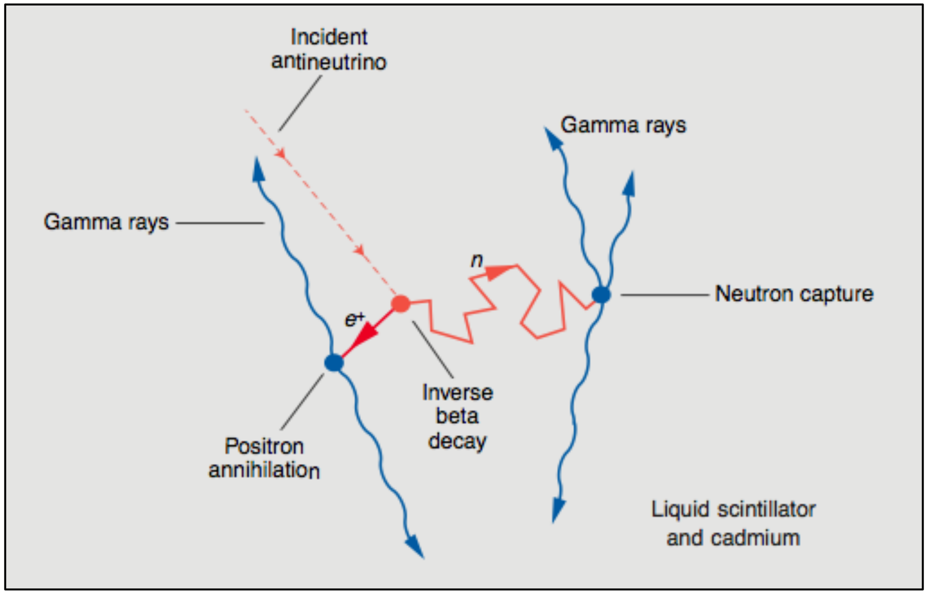
$$N_{\bar{\nu}} \approx 5.6 \times 10^{20}\, s^{-1}\ in\ 4\pi$$

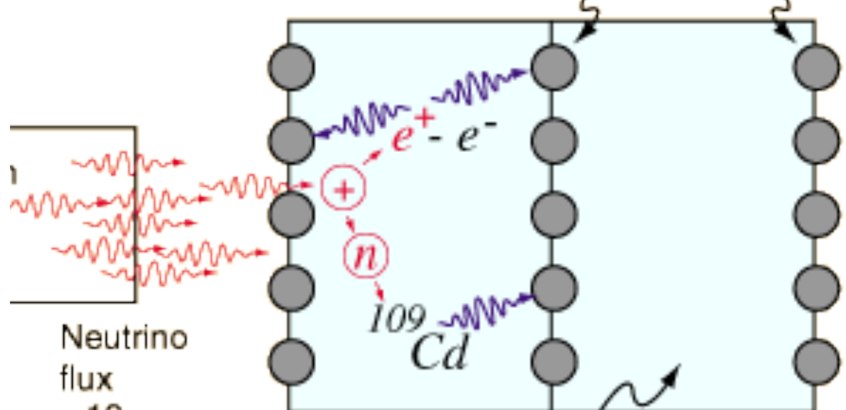
- Fred Reines and Clyde Cowan used the nuclear power reactor at Savannah River as an intense source and the inverse β-decay reaction to try to detect the ν_e

Persistence Pays Off

- Finally, confirmation in 1956

$$\bar{\nu}_e + p \rightarrow e^+ + n$$





Positron annihilates promptly on electron to produce two 0.5 MeV Gamma rays

Neutron gets captured by Cadmium nucleus after a delay of ~5 microseconds

Persistence Pays Off

"[Prof. Pauli], we are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons."

- **Fred Reines and Clyde Cowan** (1956)

"Everything comes to him who knows how to wait."

- **Wolfgang Pauli** (1956)

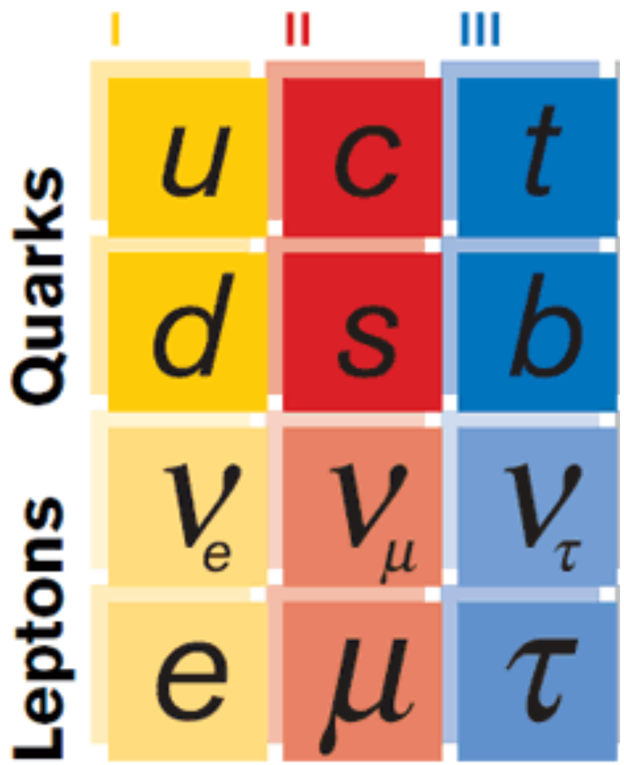
It took 25 years to detect the first of Pauli's neutrino!

Flavor and Families in the SM

- In 1962 Schwartz, Lederman and Steinberger established the existence of a <u>second, distinct type of neutrino</u> that made muons instead of electrons when they interact

- This discovery was really the first indication of the <u>"family" structure</u> in the Standard Model

- The third (and last?) neutrino was not directly detected until 2000 by the DONUT experiment at Fermilab (<u>70 years</u> after the Pauli hypothesis)



Three Generations of Matter

The Modern Weak Interaction

- Taking another look at Fermi's theory of the weak interaction:

$$M_{weak-CC} = G_F\left(\bar{u}_n\gamma^\mu u_p\right)\left(\bar{u}_\nu\gamma_\mu u_e\right)$$

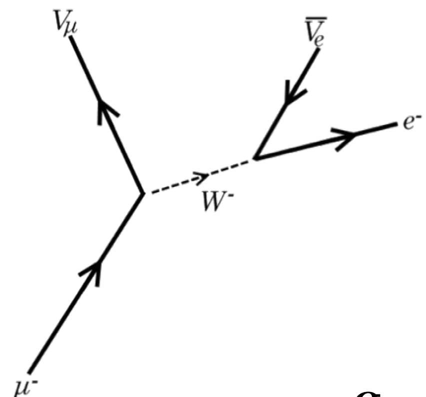
- Note the absence of a propagator term. Of course, we now know that the weak force, like the EM one, is <u>mediated by the exchange of weak bosons</u>, the $W^\pm$ and Z

- We also know that the assumption of pure vector-vector was incorrect, the <u>weak force violates parity</u> and so the vertex factors are not simply γ_μ, but include both vector-vector and vector-axial coupling contributions

$$\gamma_\mu \rightarrow \gamma_\mu\left(1-\gamma^5\right)$$

The Modern Weak Interaction

- An example, the decay of muons:



$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

q^2: 4-momentum carried by the exchange particle

M: mass of exchange particle

$$M_{\mu-decay} = \frac{g_w}{\sqrt{2}}\left[\overline{u}_{\nu_\mu}\gamma^\mu\left(1-\gamma^5\right)u_\mu\right]\left(\frac{1}{M_W^2-q^2}\right)\left[\overline{u}_e\gamma_\mu\left(1-\gamma^5\right)u_{\overline{\nu}_e}\right]$$

- Fermi's original theory essentially buried the propagator, vertex terms, and a dimensionless constant (g_w here) into the constant G_F

- But in many experimental cases $\underline{\underline{q^2 << M_W{}^2}}$, making Fermi's theory an excellent approximation

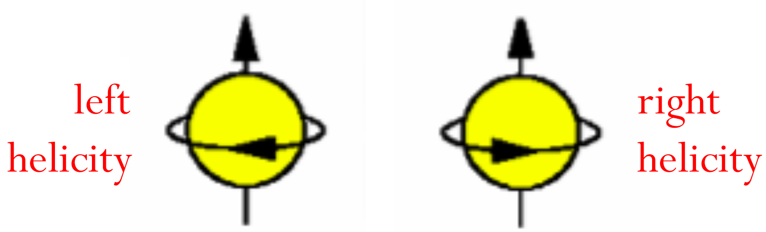
Helicity, Chirality, and Parity

The Weak force is "left-handed"

$$\frac{1}{2}\left(1-\gamma^5\right)\psi = \psi_L$$

$(1-\gamma^5)$ is projection operator onto the left-handed states for fermions and right-handed states for anti-fermions

- **Helicity**
  - Projection of spin along the particle's momentum vector



  - Frame dependent for massive particles (can always boost to a frame faster than the particle, reversing helicity)

- **Chirality ("Handedness")**
  - Lorentz invariant counterpart to helicity
  - Same as helicity for massless particles
  - Since neutrinos created by weak force
    - all neutrinos are left-handed
    - all antineutrinos are right-handed
  - Only left-handed charged leptons participate in weak interactions. Small right-helicity contribution $\propto m/E$

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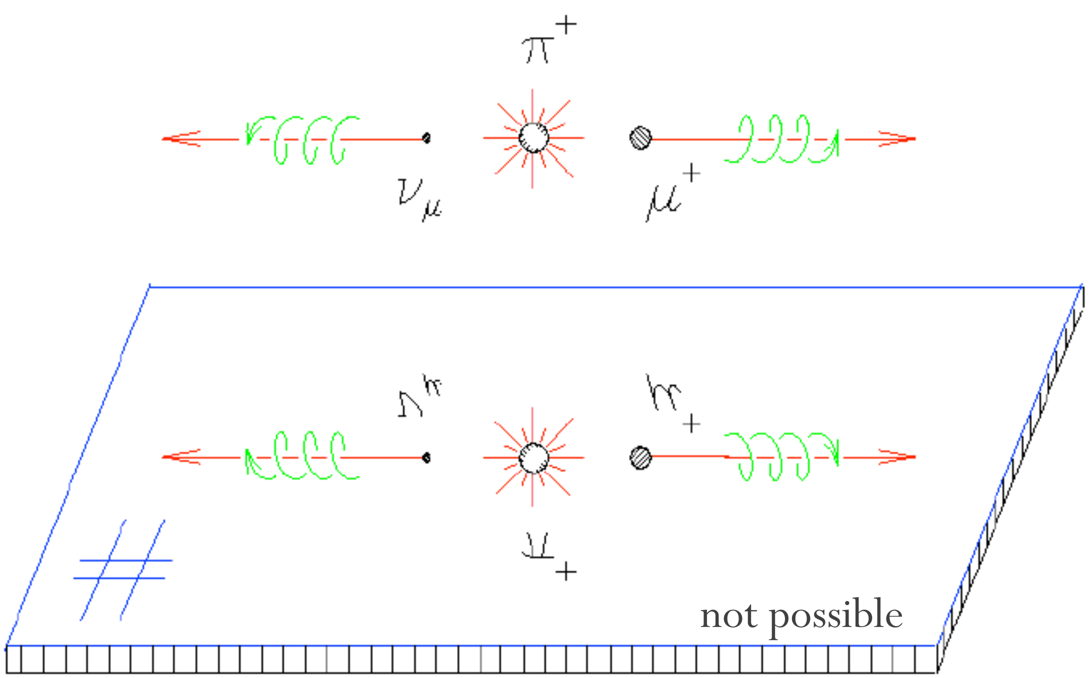

$$R_\pi = \frac{\Gamma\left(\pi^+ \to e^+\nu_e\right)}{\Gamma\left(\pi^+ \to \mu^+\nu_\mu\right)}$$

$$R_\pi = \left(\frac{m_e}{m_\mu}\right)^2\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 = 1.23\times10^{-4}$$

Strength of the Weak Interaction

- Using the low q^2 approximation and the value of G_F we got from the muon lifetime and mass:

$$\frac{G_F}{(\hbar c)^3} = 1.166 \times 10^{-5} / GeV^2 = \frac{\sqrt{2}}{8}\left(\frac{g_w}{M_W c^2}\right)^2$$

Once it was realized there is a massive propagator, one can calculate the intrinsic strength of the weak interaction…

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$$M_W \approx 80\ GeV/c^2 \quad \Rightarrow \quad g_w \approx 0.7$$

$$if \qquad \alpha = \frac{g_e^{\ 2}}{4\pi} = \frac{1}{137}, \qquad \alpha_w = \frac{g_w^2}{4\pi} = \frac{1}{29}$$

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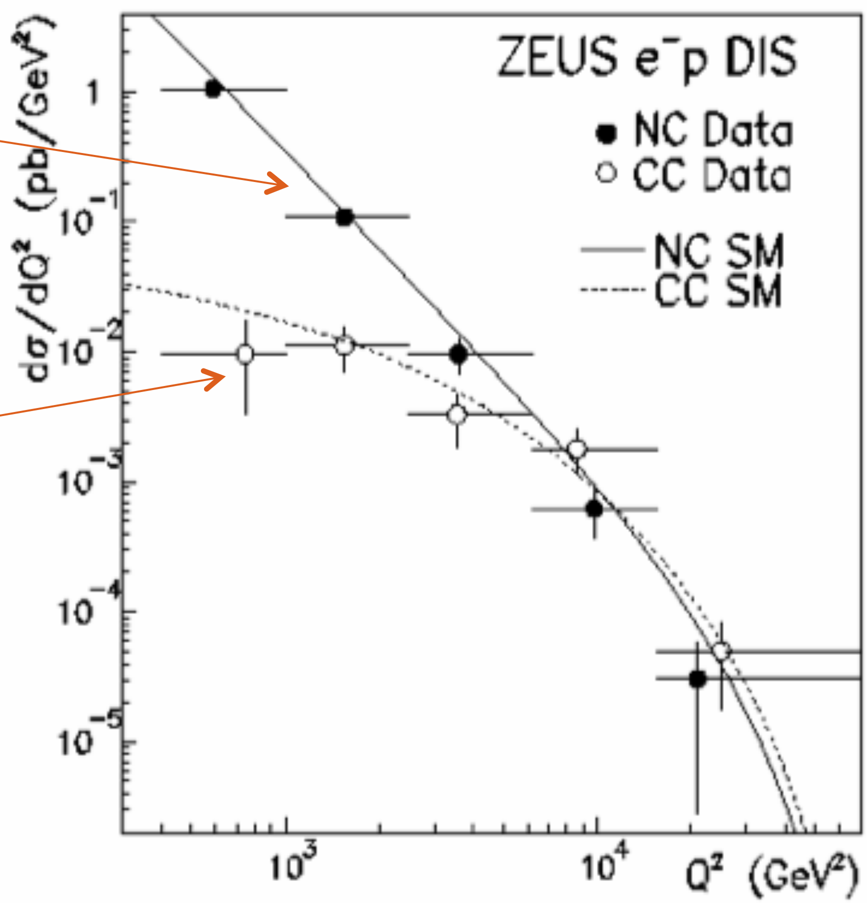
The Weak Interaction coupling constant is <u>the same order</u> as the electromagnetic!!

Strength of the Weak Interaction

- And at sufficiently high center of mass energy, the weak interaction becomes as strong as the EM!

NC dominated by EM interactions (photon exchange) $\sim 1/q^2$

CC due to interaction via W boson $\sim 1/(q^2 - M_W^2)$



ZEUS an experiment at HERA, a high energy electron-proton collider

Electromagnetism / Electroweak

- University of Wisconsin's own F. Halzen makes a very nice analogy in *Quarks and Leptons* between the unification of electromagnetic and weak interactions and the original unification of EM

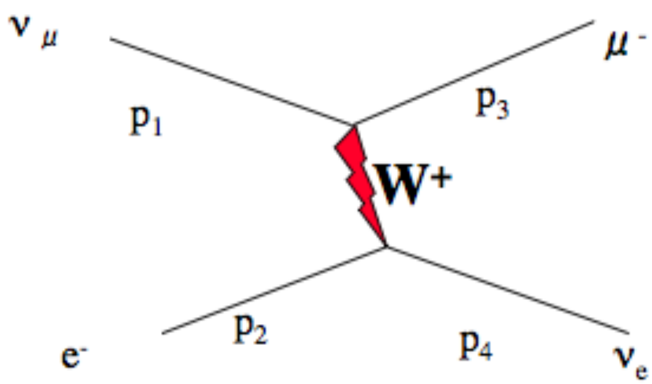
> *"We may think of $g_e \approx g_w$ as a unification of weak and electromagnetic interactions in much the same way as the unification of the electric and magnetic forces in Maxell's theory of electromagnetism, where*
>
> $$\mathbf{F} = e\mathbf{E} + e_M\, \mathbf{v}\ x\ \mathbf{B}$$
>
> *with $e_M = e$. At low velocities, the magnetic forces are very weak, whereas for high-velocity particles, the electric and magnetic forces play a comparable role. The velocity of light c is the scale which governs the relative strength. The analogue for the electroweak force is M_W on the energy scale."*

What happens when we are at energies significantly below the M_W scale?

Strength of the Weak Interaction

- Why so "weak" for neutrino interactions?

- For example, neutrino-electron scattering: $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$



$$
\begin{aligned}
s &\equiv (p_1 + p_2)^2 \\
&= (E_\nu + m_e)^2 - (\vec{p}_\nu)^2 \\
&= E_\nu^2 - p_\nu^2 + m_e^2 + 2E_\nu m_e \approx 2E_\nu m_e
\end{aligned}
$$

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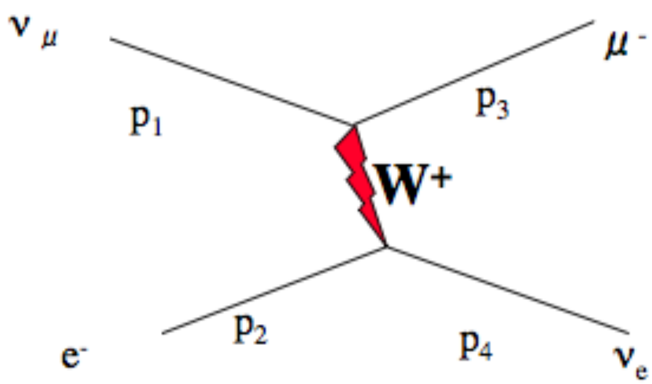

$$s \equiv (p_1 + p_2)^2$$
$$= (E_\nu + m_e)^2 - (\vec{p}_\nu)^2$$
$$= E_\nu^2 - p_\nu^2 + m_e^2 + 2E_\nu m_e \approx 2E_\nu m_e$$

- For a real experiment, neutrino energy may be order 100 GeV:

$$E_{CM} = s \approx 2E_\nu m_e = 2 * 100 * .000511 \approx \boxed{0.1\,GeV}$$

Strength of the Weak Interaction

- Why so "weak" for neutrino interactions?

$$\frac{d\sigma}{dq^2} \propto \frac{1}{(M^2 - q^2)^2}$$

q^2 is 4-momentum carried by the exchange particle

M is mass of the exchange particle

$$M_W \approx 80\ GeV/c^2$$

Need to create this to mediate the interaction, but only had 0.1 GeV

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Need to create this to mediate the interaction, but only had 0.1 GeV

Where to get the additional needed energy from?

Take out a loan…

Strength of the Weak Interaction

At low center of mass energies, we borrow it from the vacuum for a short time!

$$\Delta E \Delta t \geq \frac{\hbar}{2} \qquad t \sim \frac{\hbar}{\Delta E}$$

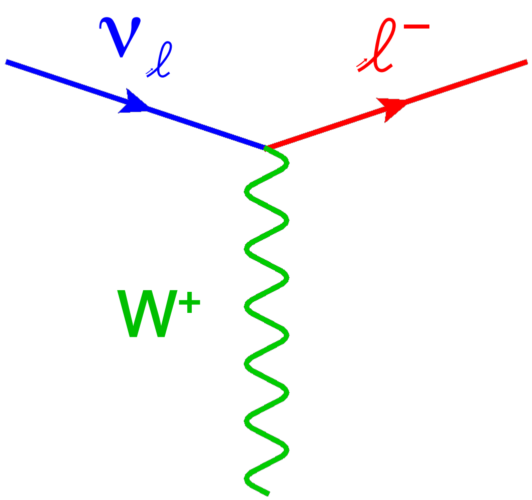
To make a W boson, we'll need to borrow $80\ GeV/c^2$, $t \sim 8 \times 10^{-27}\ s$

Which explains the very short range of the weak interaction at low energies, $d = tc \sim 2.4 \times 10^{-18}\ m$

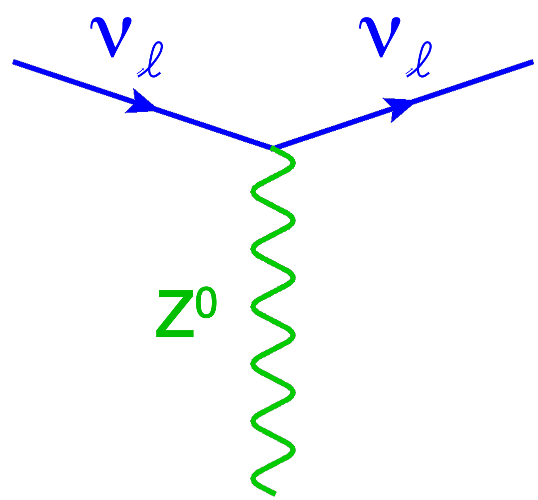
Two Types of Weak Interactions

$W^{\pm}$ exchange constitutes a "charged-current" interaction

Z^0 exchange constitutes a "neutral-current" interaction



Charged-Current (CC)



Neutral-Current (NC)

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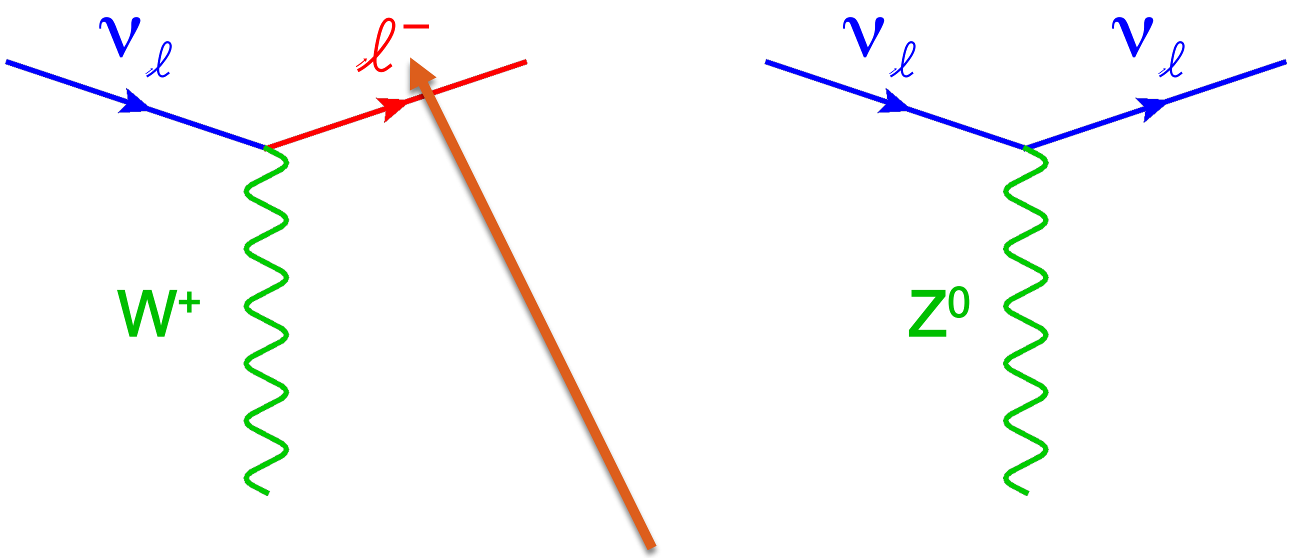

Flavor of outgoing
charged lepton determines
flavor of neutrino

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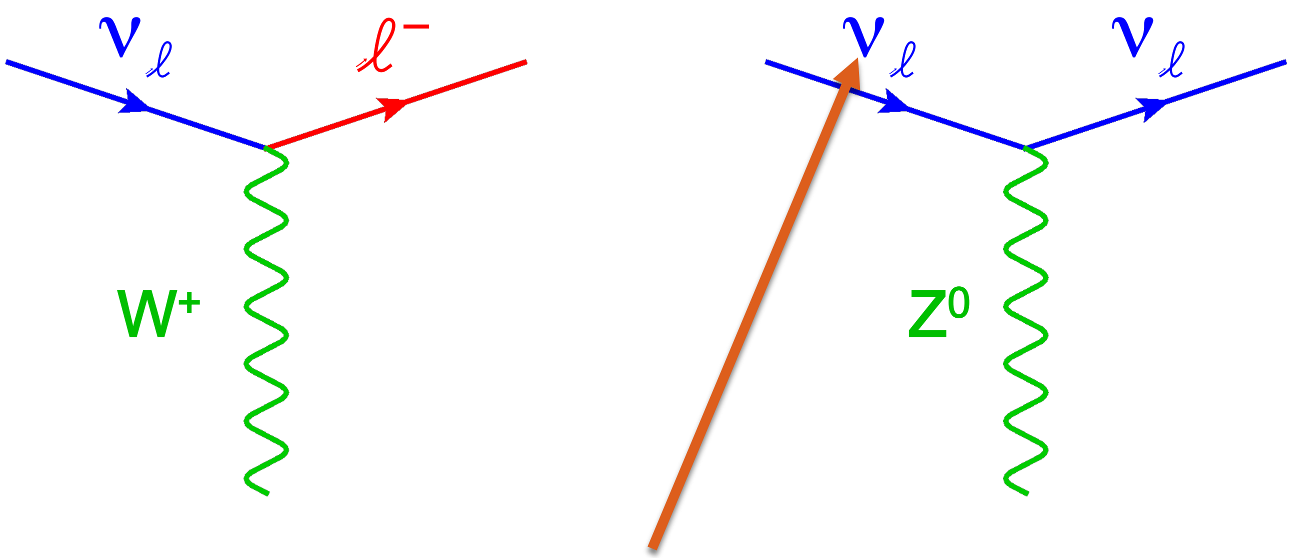

No way to determine flavor in neutral-current interaction

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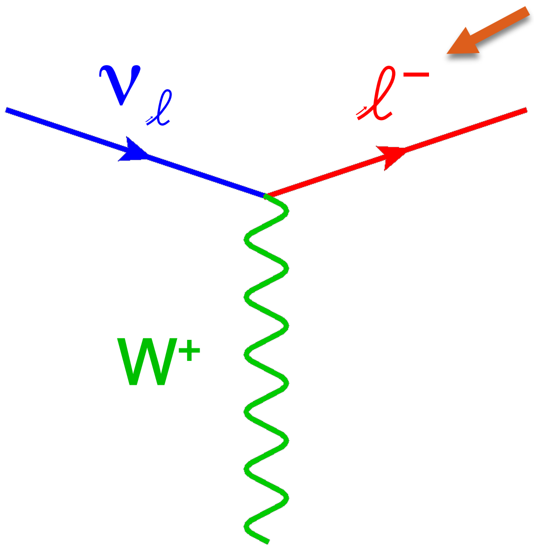
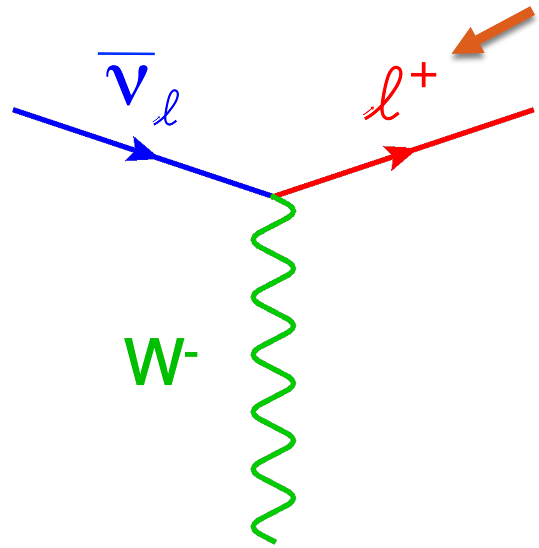
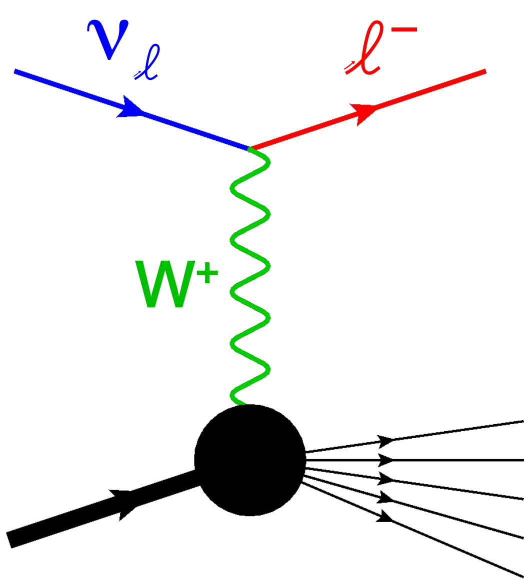




Sign of outgoing
charged lepton determines
<u>neutrino vs. antineutrino</u>

Neutrino-Nucleon Interactions

- The lepton vertex was pretty simple. Of course, it's the hadronic vertex in ν-N scattering that contains all the complication



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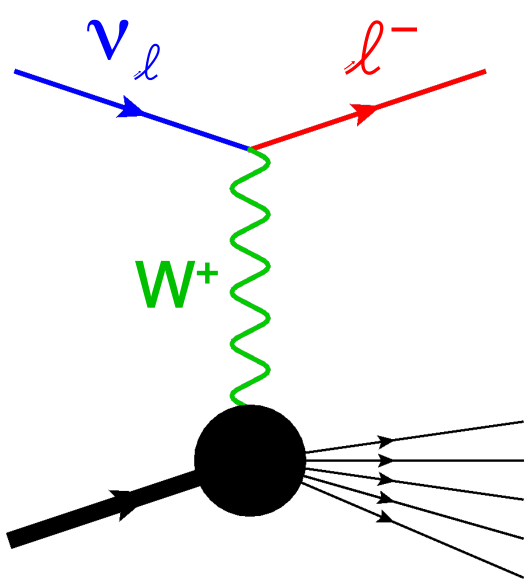

✓ Quasi-Elastic Scattering (QE)

- target changes (CC) but no break up

$$\nu_\mu + n \rightarrow \mu^- + p$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

✓ Nuclear Resonance Production

- target goes to excited state

$$\nu_\mu + N \rightarrow N^*(\Delta) \rightarrow \mu + N + \pi$$

✓ Deep-Inelastic Scattering (DIS)

- nucleon breaks up completely

$$\nu_\mu + quark \rightarrow \mu + X$$

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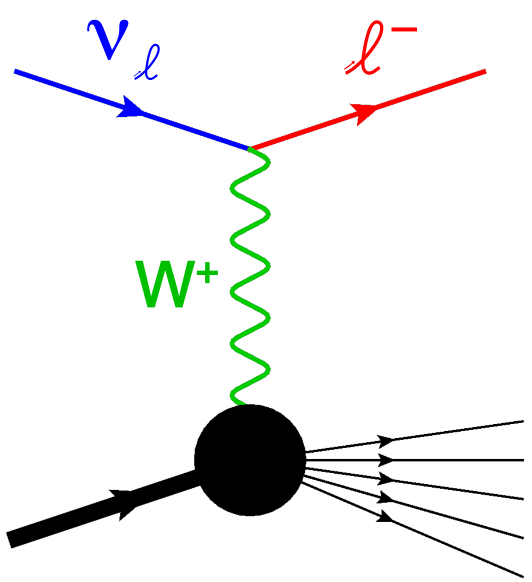
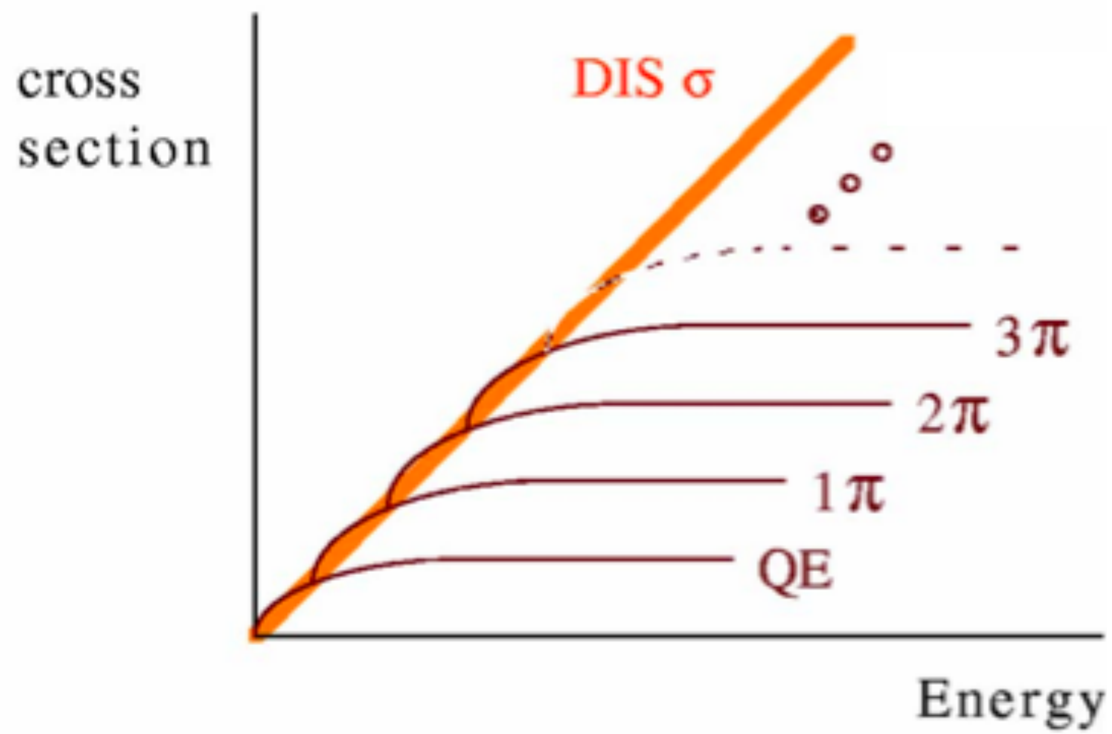
- The lepton vertex was pretty simple. Of course, it's the hadronic vertex in ν-N scattering that contains all the complication

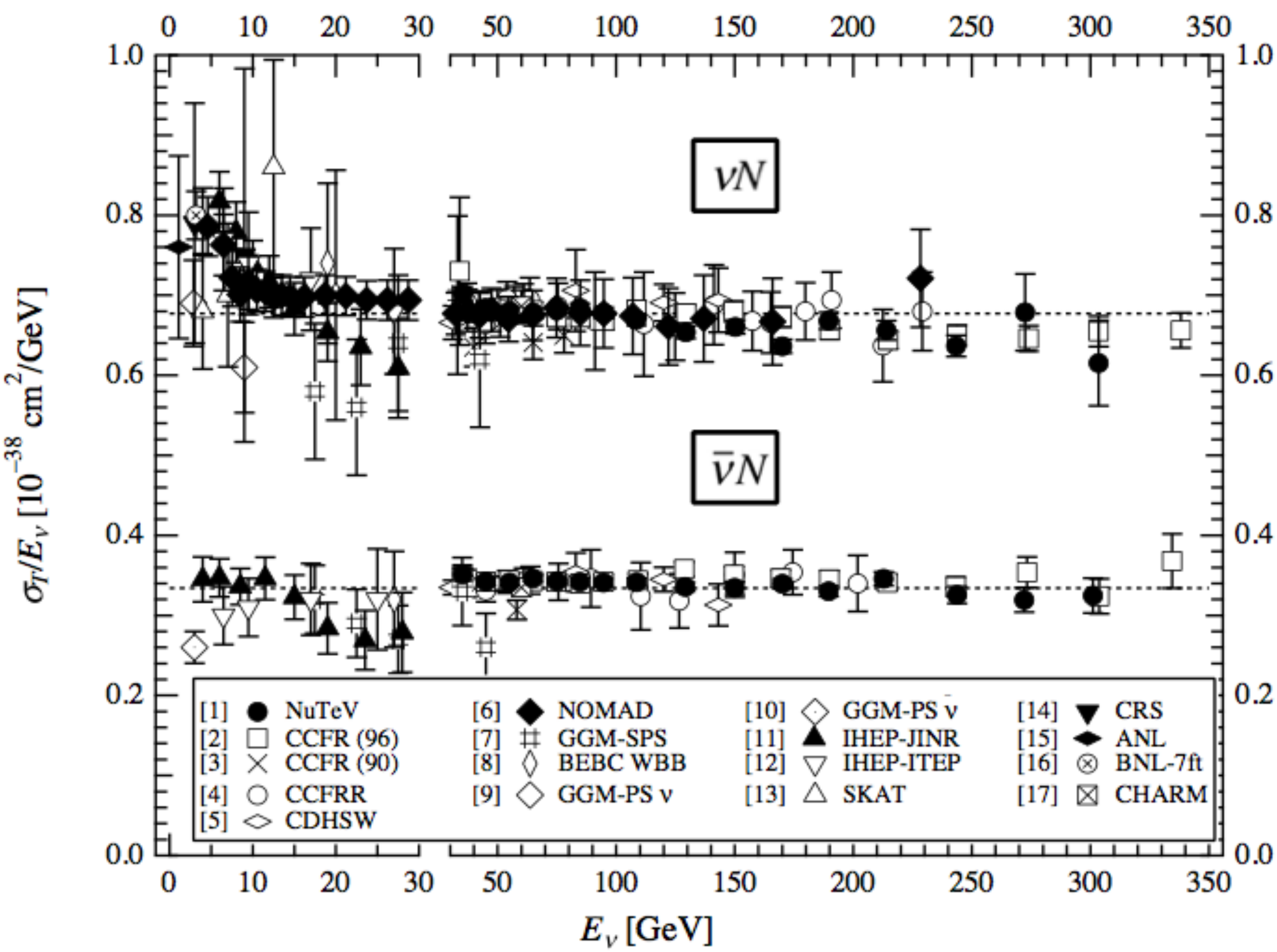




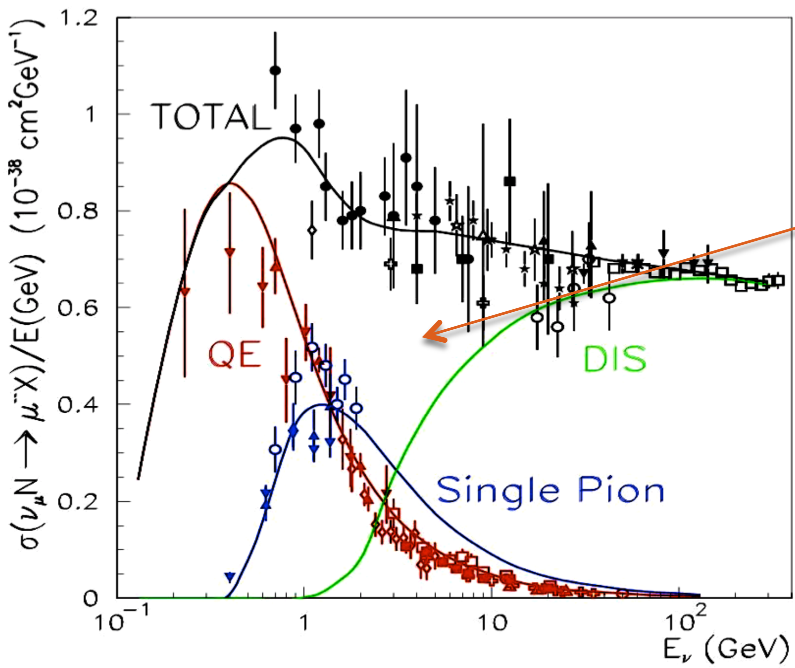
ν_μ Total CC/NC Cross Sections

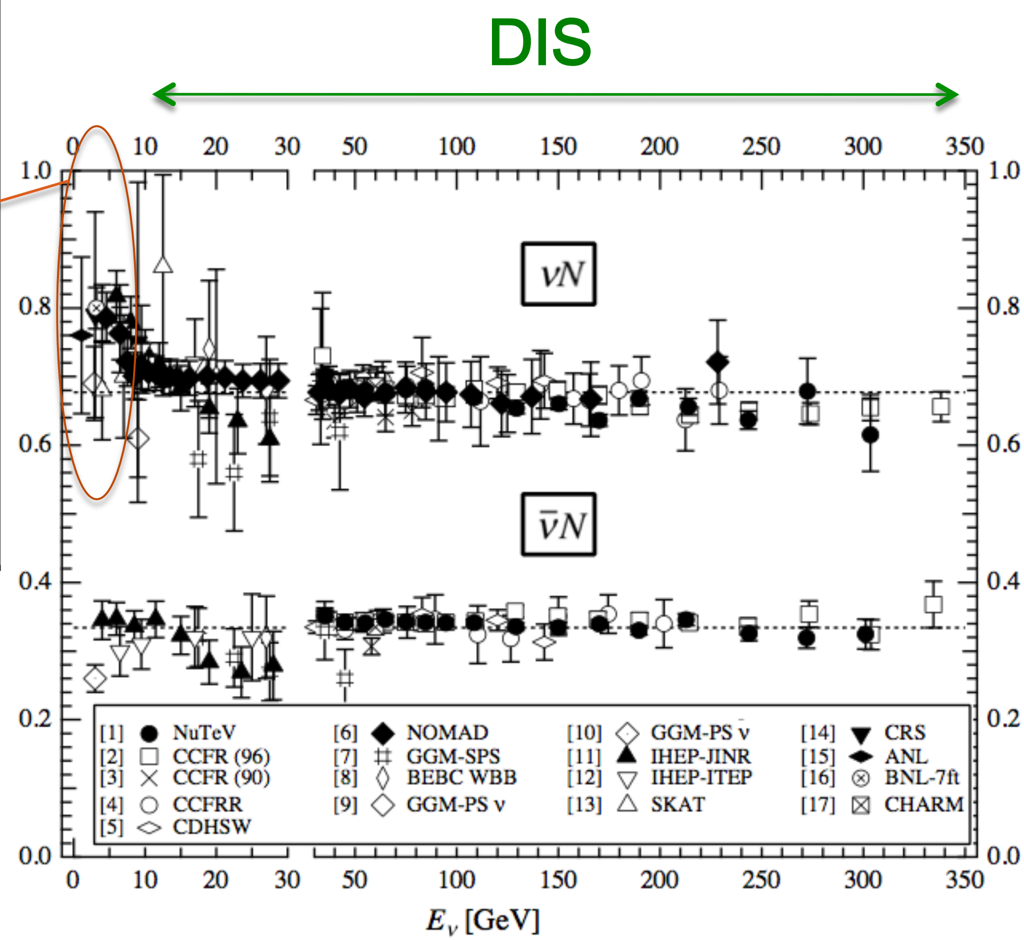
- Indeed the cross section rises linearly with energy

Note the division by E_ν on this axis: σ/E_ν



ν_μ Total CC/NC Cross Sections



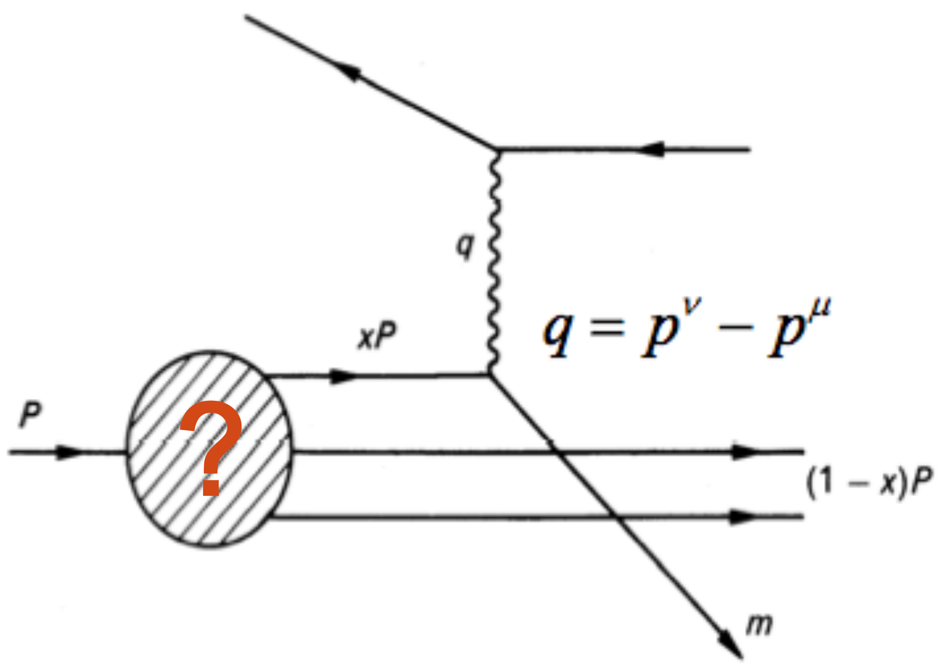


Only in lowest energy region (few GeV) does non-DIS cross section dominate

Probing Nucleon Structure with Neutrinos

Neutrinos provide a unique weak probe complimentary to the wealth of charged lepton DIS data (Cynthia Keppel's lecture last week)

In the quark parton model, the neutrino scatters off an individual parton inside the nucleon, which carries a fraction, x, of the nucleon's total momentum



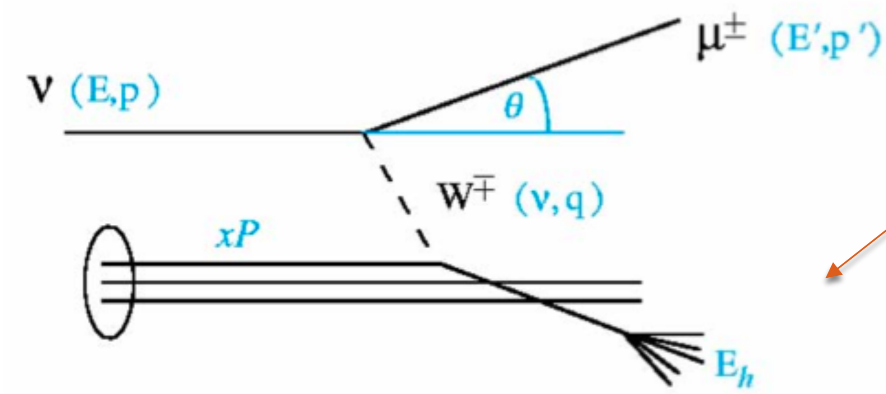
mass of target quark:

$$m_q^2 = x^2 P^2 = x^2 M_T^2$$

mass of final state quark:

$$m_{q'}^2 = \left(xP + q\right)^2$$

Kinematic Variables of Neutrino DIS



observables:

$$E_\mu,\ \theta,\ E_h$$

$$E_\nu = E_\mu + E_h - M_T$$

momentum transfered between ν and quark, Q^2: $\quad Q^2 = -q^2 = -(p-p')^2 = 4E_\nu E_\mu \sin^2\left(\frac{\theta}{2}\right)$

energy transfered from ν to quark, ν : $\quad \nu = E_\nu - E_\mu = E_h - M_T$

fraction of nucleon momentum carried by quark, x : $\quad x = \frac{Q^2}{2M_T\nu}$

fraction of available energy transfered to quark, y : $\quad y = \frac{\nu}{E_\nu} = 1 - \frac{E_\mu}{E_\nu} = \frac{Q^2}{2M_T E_\nu x} \approx \frac{1}{2}(1-\cos\theta)$

recoil mass squared, W^2: $\quad W^2 = -Q^2 + 2M_T\nu + M_T^2$

Parton Distribution Functions $q(x)$

- Charge and helicity considerations impose important restrictions on possible neutrino-quark interactions
- Key point is that neutrinos and antineutrinos sample different quark flavor content of nucleon substructure
  - neutrinos only interact with : $d,\ s,\ \bar{u},\ \bar{c}$
  - antineutrinos only interact with : $u,\ c,\ \bar{d},\ \bar{s}$

$$\frac{d\sigma}{dxdy}(\nu + proton) = \frac{G_F^2 s}{\pi} x\left[d(x) + s(x) + \left[\bar{u}(x) + \bar{c}(x)\right](1-y)^2\right]$$

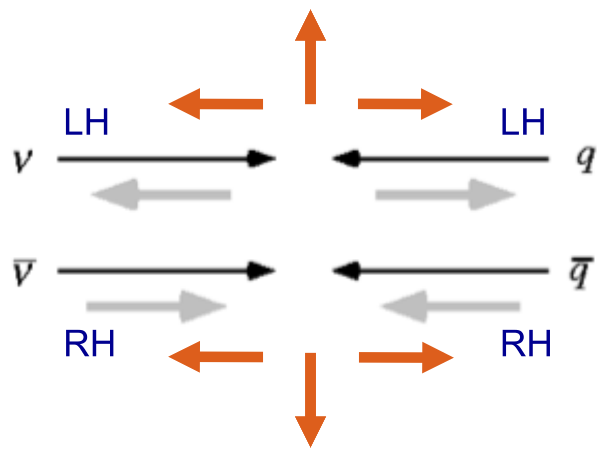
$$\frac{d\sigma}{dxdy}(\bar{\nu} + proton) = \frac{G_F^2 s}{\pi} x\left[\bar{d}(x) + \bar{s}(x) + \left[u(x) + c(x)\right](1-y)^2\right]$$

Parton Distribution Functions $q(x)$

- Charge and helicity considerations impose important restrictions on possible neutrino-quark interactions

neutrino
+quark

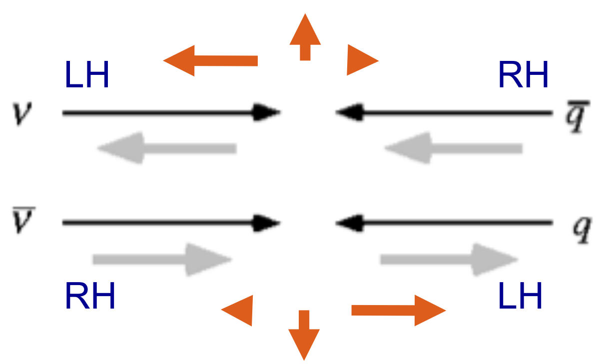
antineutrino
+antiquark



$$\frac{d\sigma}{dy}(\nu q) = \frac{d\sigma}{dy}(\bar{\nu}\bar{q}) = \boxed{\frac{G_F^2 sx}{\pi}}$$

neutrino
+antiquark

antineutrino
+quark

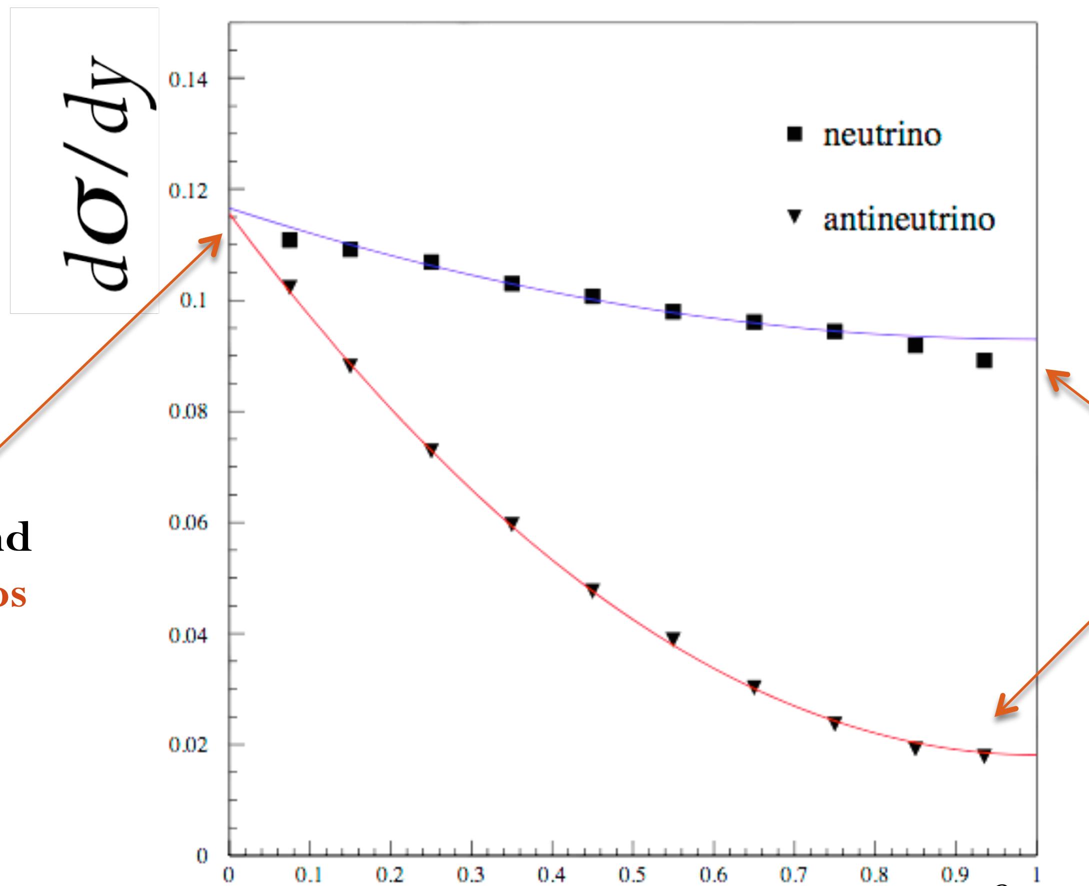


$$\frac{d\sigma}{dy}(\bar{\nu} q) = \frac{d\sigma}{dy}(\nu \bar{q}) = \boxed{\frac{G_F^2 sx}{\pi}(1-y)^2}$$

$$1 - y \approx \frac{1}{2}(1 + \cos\theta)$$

Parton Distribution Functions $q(x)$

Neutrino CC DIS cross section vs. y



$\theta = 0$ $\theta = \pi$

$$y = (1 - \cos\theta)/2$$

y = 0

neutrinos and antineutrinos the same

y = 1

neutrinos only see quarks

antineutrinos only see antiquarks

Nucleon Structure Functions

- Can also write the ν-N cross section in a model-independent way using three "nucleon structure functions", F_1, F_2, and xF_3 :

$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{dxdy} = \frac{G_F^2 M_T E}{\pi}\left[xy^2 F_1(x,Q^2) + \left(1 - y - \frac{xyM_T}{2E}\right)F_2(x,Q^2) \pm y\left(1-\frac{y}{2}\right)xF_3(x,Q^2)\right]$$

- We'll use the Callan-Gross relation to rewrite the expression

$$R \equiv \left(1 + \frac{4M_T^2 x^2}{Q^2}\right)\frac{F_2}{2xF_1} - 1$$

- The functions $F_2(x,Q^2)$, $xF_3(x,Q^2)$, and $R(x,Q^2)$ can then be mapped out experimentally from the measured DIS differential cross section:

$d\sigma/dy$ in bins of (x,Q^2)

Nucleon Structure Functions

neutrino

$$\frac{d^2\sigma^{\nu A}}{dxdy} \propto \left[F_2^{\nu A}\left(x,Q^2\right) + xF_3^{\nu A}\left(x,Q^2\right)\right] + \left(1-y\right)^2\left[F_2^{\nu A}\left(x,Q^2\right) - xF_3^{\nu A}\left(x,Q^2\right)\right] + f\left(R\right)$$

antineutrino

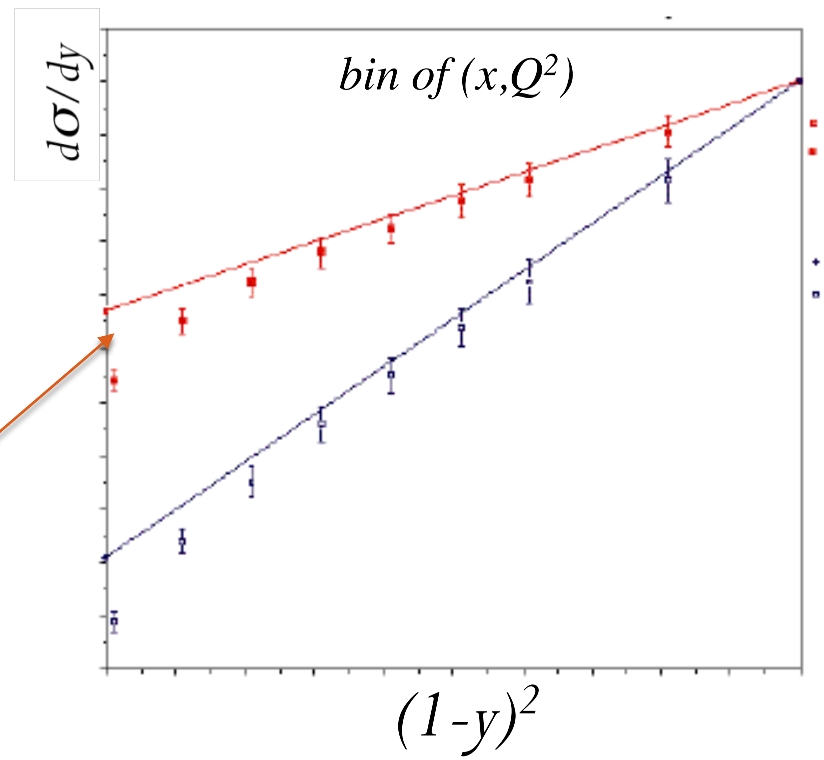
$$\frac{d^2\sigma^{\bar{\nu} A}}{dxdy} \propto \left[F_2^{\bar{\nu} A}\left(x,Q^2\right) - xF_3^{\bar{\nu} A}\left(x,Q^2\right)\right] + \left(1-y\right)^2\left[F_2^{\bar{\nu} A}\left(x,Q^2\right) + xF_3^{\bar{\nu} A}\left(x,Q^2\right)\right] + f\left(R\right)$$

<u>Equations of lines!</u>

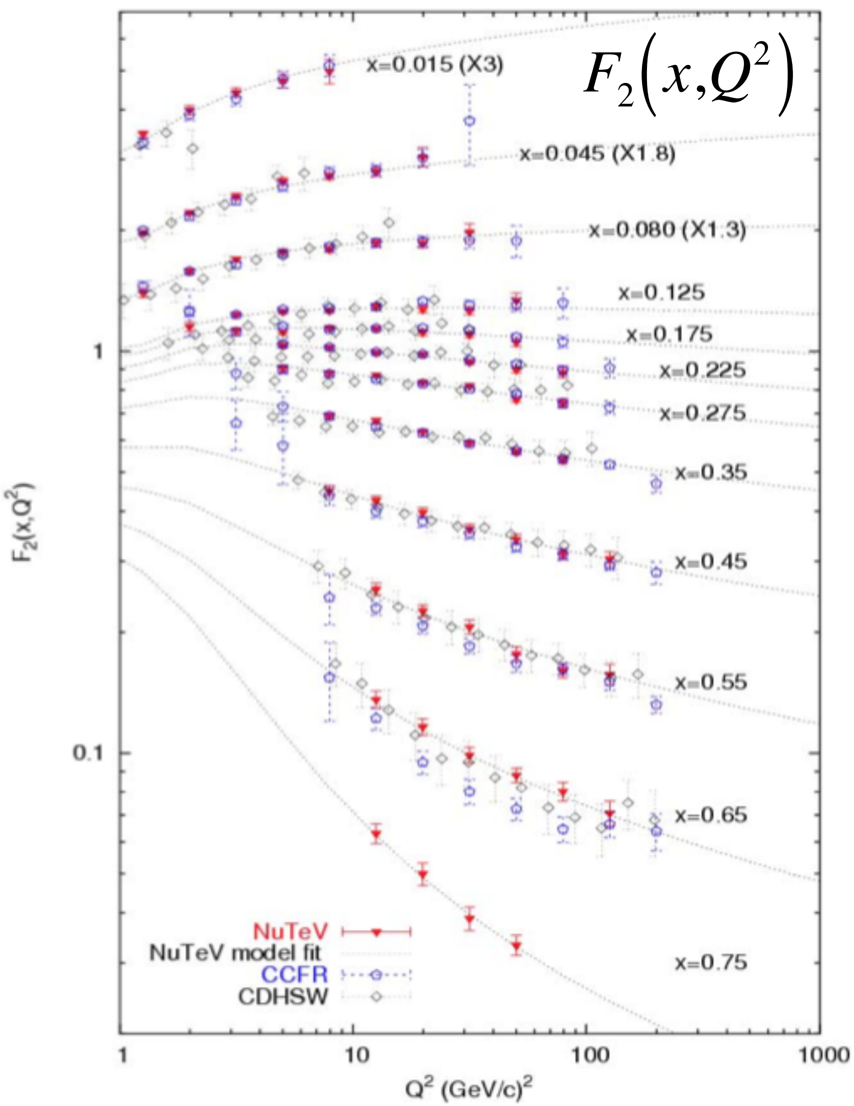
$$y \propto b + mx$$

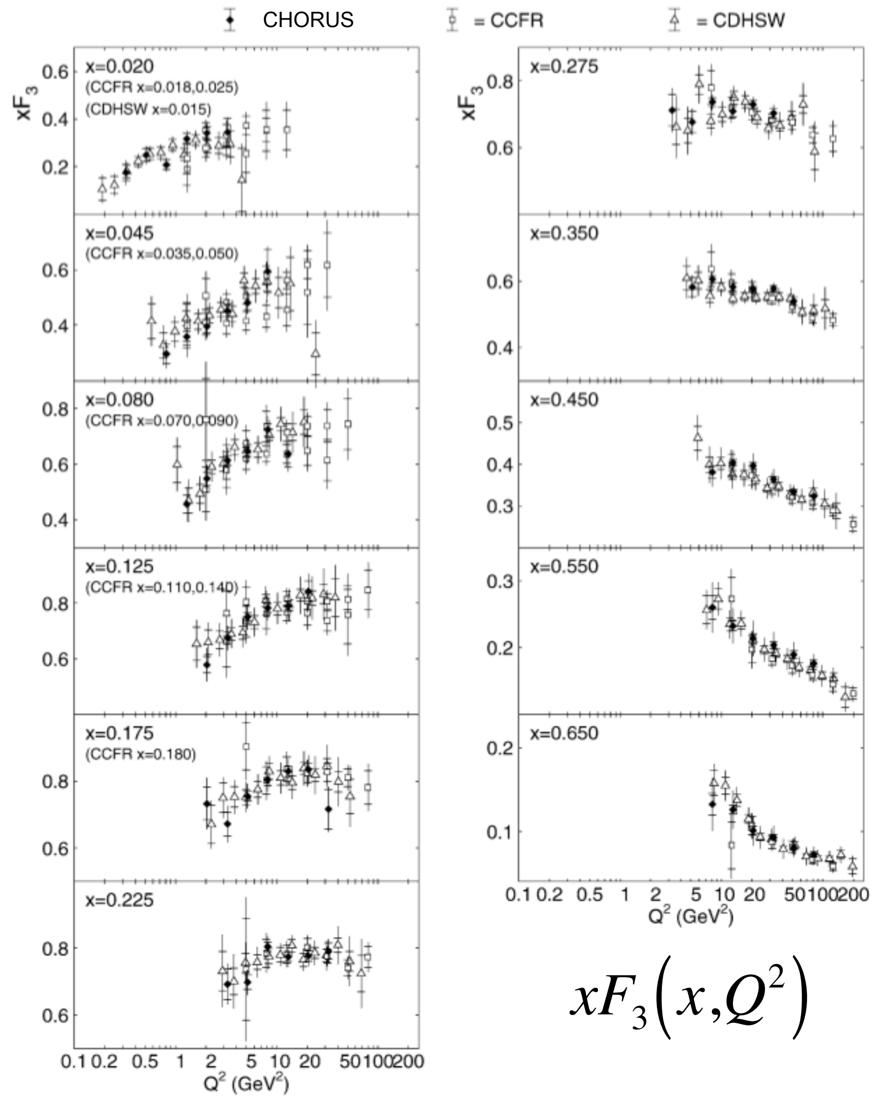
Fit for parameters F_2, xF_3 in bins of (x,Q^2)

R related to excursions from a straight line shape



Nucleon Structure Functions





Relating SFs to PDFs

- Using leading order expressions can relate the structure functions (SFs) to the parton distribution functions (PDFs)

$$F_2^{\nu N}(x,Q^2) = x\left[u + \bar{u} + d + \bar{d} + 2s + 2\bar{c}\right]$$

$$F_2^{\bar{\nu} N}(x,Q^2) = x\left[u + \bar{u} + d + \bar{d} + 2\bar{s} + 2c\right]$$

$$xF_3^{\nu N}(x,Q^2) = x\left[u - \bar{u} + d - \bar{d} + 2s - 2\bar{c}\right]$$

$$xF_3^{\bar{\nu} N}(x,Q^2) = x\left[u - \bar{u} + d - \bar{d} - 2\bar{s} + 2c\right]$$

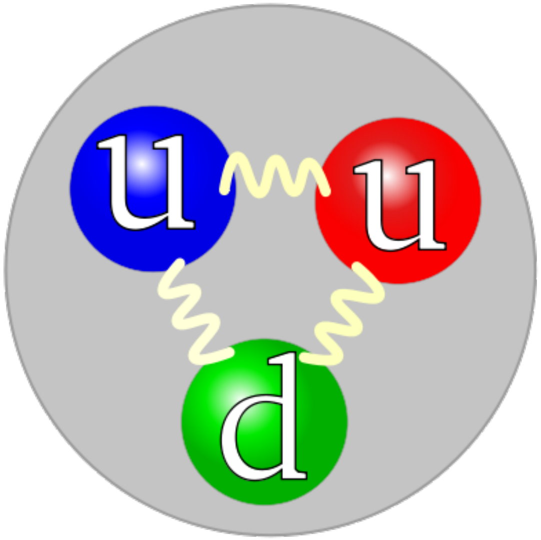
- Assuming c = $\bar{c}$ and s = $\bar{s}$

$$F_2^{\nu} - xF_3^{\nu} = 2\left(\bar{u} + \bar{d} + 2\bar{c}\right) = 2U + 4\bar{c}$$

$$F_2^{\bar{\nu}} - xF_3^{\bar{\nu}} = 2\left(\bar{u} + \bar{d} + 2\bar{s}\right) = 2U + 4\bar{s}$$

$$xF_3^{\nu} - xF_3^{\bar{\nu}} = 2\left[\left(s + \bar{s}\right) - \left(c + \bar{c}\right)\right] = 4\bar{s} - 4\bar{c}$$

Parton Distribution Functions $q(x)$

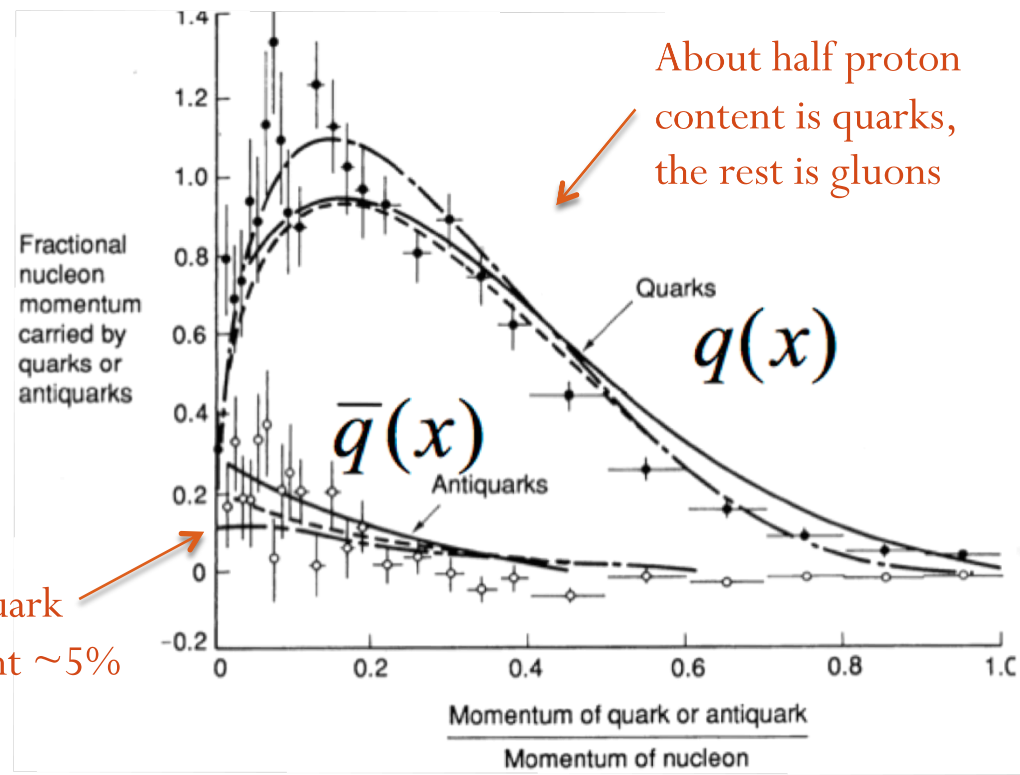


$$\frac{d\sigma}{dxdy}(\nu + proton) = \frac{G_F^2 xs}{2\pi}\left[Q(x) + (1-y)^2 \overline{Q}(x)\right]$$

$$\frac{d\sigma}{dxdy}(\overline{\nu} + proton) = \frac{G_F^2 xs}{2\pi}\left[\overline{Q}(x) + (1-y)^2 Q(x)\right]$$

If there were only the valence quarks ($\overline{Q}$=0)

$$\frac{\sigma(\overline{\nu})}{\sigma(\nu)} = \frac{\int_0^1 dy(1-y)^2}{\int_0^1 dy} = \frac{1}{3}$$

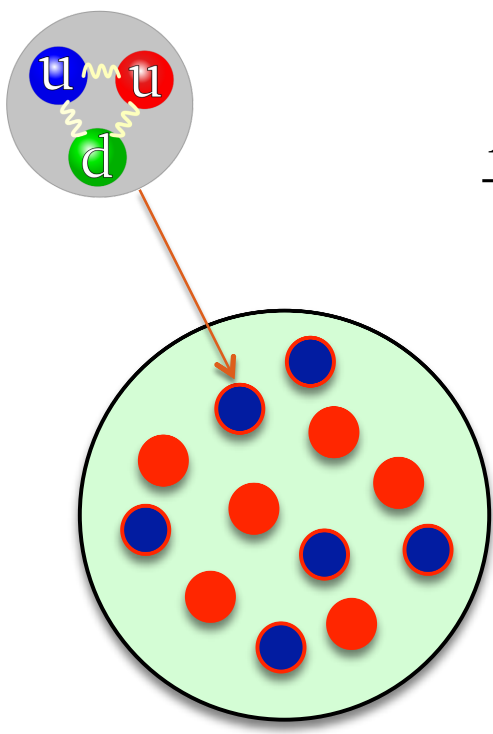


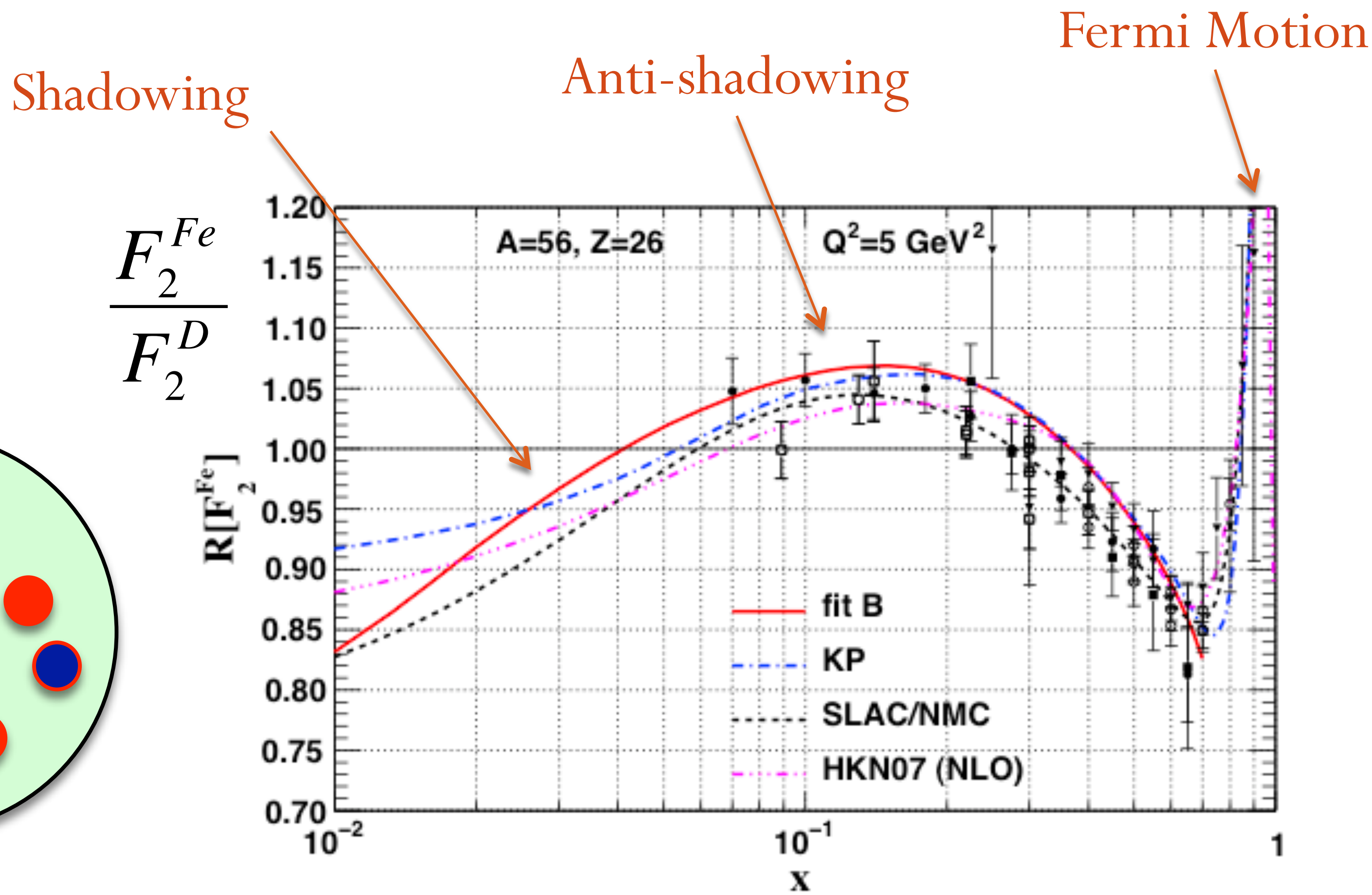
About half proton content is quarks, the rest is gluons

Antiquark content ~5%

Probing Nuclear Effects with Neutrinos

- Effects of the nuclear medium accessed by comparing structure functions measured on high and low A targets



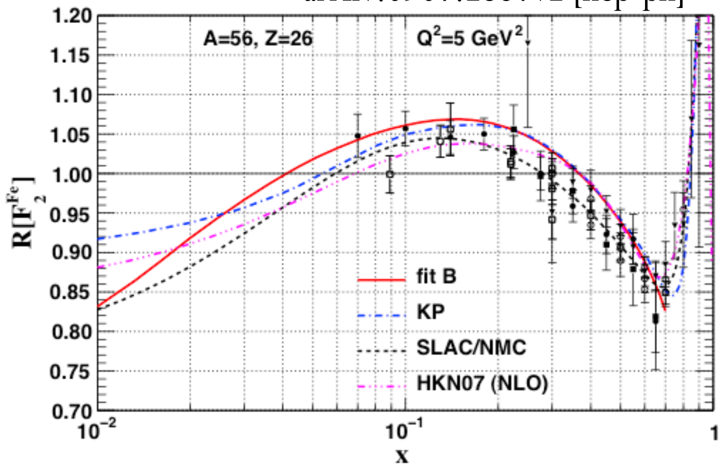


Probing Nuclear Effects with Neutrinos

- Most neutrino scattering data data off targets of large A (Ca,Fe)

- Recent studies indicate that nuclear corrections in ℓ^{+}-A (charged lepton) and ν-A (neutrino) scattering <u>may not be the same</u>

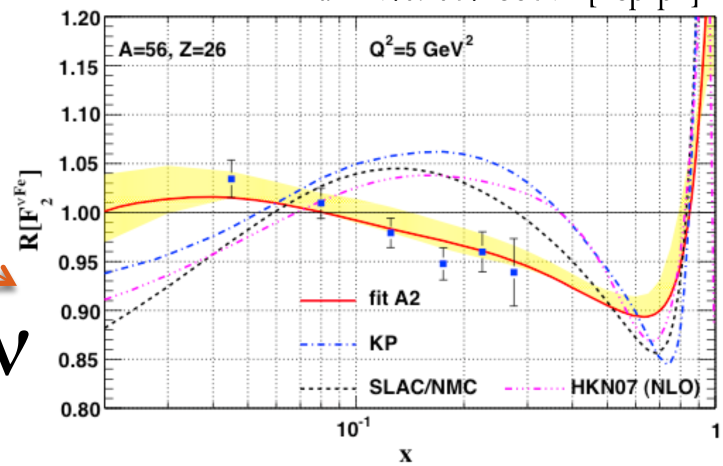
arXiv:0907.2357v2 [hep-ph]



$$\frac{F_2^{Fe}}{F_2^{D}}$$

ℓ^{+} ν

arXiv:0907.2357v2 [hep-ph]



- Need data across a range of A to extract nuclear effects (MINERνA)

Summary I

- Neutrinos provide an important weak force probe of matter
  - Neutrinos and antineutrinos “taste” different quark flavor content
    - neutrinos only interact with : $d, s, \bar{u}, \bar{c}$
    - antineutrinos only interact with : $u, c, \bar{d}, \bar{s}$
  - Angular distributions of neutrino/antineutrino DIS interactions affected by left-handedness of weak interaction
    - $\sigma(\bar{\nu} q) = \sigma(\nu q)(1-y)^2$
- Neutrinos and the weak interaction are critical players in many processes in the universe
- But what do we know about the neutrino itself….?

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  - Sam Zeller (Fermilab)
  - Kevin McFarland (University of Rochester)
  - Bonnie Fleming (Yale)

- Useful references for further reading:

  - K. Zuber, *Neutrino Physics*, 2004
  - J. Thomas, P. Vahle, *Neutrino Oscillations: Present Status and Future Plans*, 2008
  - F. Close, *Neutrino*, 2010
  - F. Halzen, *Quarks and Leptons*, 1984